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**Design of a 5,000 K. W.**

**Induction Motor**

**Electrical Engineering**

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# DESIGN OF A 5,000 K. W. INDUCTION MOTOR

BY

ELMER LEROY JOHNSON

CECIL DOUGLAS HENRY

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THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

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COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

1911



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May 31

1901

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Elmer Leroy Johnson and Cecil Douglas Henry

ENTITLED Design of a 5,000 K. W. Induction Motor

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Electrical Engineering

*S. W. Fisk.*

Instructor in Charge

APPROVED:

*Quastberg*

HEAD OF DEPARTMENT OF Electrical Engineering.

197654



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## INTRODUCTION.

In the design of alternating current generators, the tendency has been to increase the size of the units, until at present generators of 14000 K. W. are in successful operation, and still larger machines are contemplated.

However, the design of motors has generally been confined to those of comparatively small or medium horse power.

Although induction motors of 1000 or 2000 H. P. are in extensive use in the various steel mills through out the country, there are very few which exceed the above capacity.

For this reason, the design of a 5000 K. W. motor must be based on theoretical considerations, with the help of any experimental results, obtained from generators, which may be made to apply.

In commercial design, a very important practical consideration which is likely to be overlooked in theoretical calculations is the cost of the finished product.

However excellent a design may be in theory, it may be absolutely worthless, when the final cost of the machine is considered. In this connection, the experience and judgement of the designer play an important part. In general, the best theoretical machine will be entirely too expensive, while the cheapest machine which it is possible to build will probably have a very poor efficiency and would not stand the severe tests of actual service.

To secure satisfaction both in regard to first cost



and operation, it is necessary to choose a design which, in a measure combines both of these conditions. From this conclusion, a conception of the real problem in the design of a large machine is obtained. To design a motor of 5000 K. W. is a comparatively simple matter, the difficult part of the problem is to select the true design, or in other words, from the large number which might be designed for this capacity, to choose the motor which will most nearly satisfy the commercial conditions involved.

Since there are no motors of 5000 K.W. in operation, no data concerning such machines is at hand. Therefore, the only logical method of attacking this problem is to design a number of motors, and to find the effect of the variation of any one quantity upon the entire motor. In this way, by a process of elimination, the real design is found.



### CALCULATIONS INVOLVED.

Many specifications, which are either neglected or disregarded in the purchase of a smaller motor, would be demanded by any one contemplating the installation of a 5000 K. W. machine.

It is reasonable to expect that in a large unit the cost per K. W. would be lower, and the efficiency, regulation, and power factor should be better than in a machine of smaller capacity. As stated in the introduction these results can be obtained only by designing a variety of machines.

A discussion of these designs will show why a particular constant is taken, and its effect on the machine as a whole. In the following pages it is often found necessary to discuss results before taking up the method of obtaining them. In such cases a full discussion of the method involved will be found in the design of the machine. The quantities which must first be considered are the voltage and the frequency.

#### Frequency

The standard frequency for power is 25 cycles, although frequencies of 12.5 and 15 are used in Europe. By far the largest number of power lines of today operate at a frequency of 25 cycles and, in the absence of any specifications in regard to this, 25 cycles is taken as the frequency for this machine.



## Voltage.

In, general, the lower limit of the voltage used is determined by the maximum current allowable. For a 5000 K. W. motor at least 2000 volts should be used. The difficulty of insulation probably sets the upper limit at about 10000 volts. Current practice in alternators is to use a voltage... of from 5000 to 7000 .

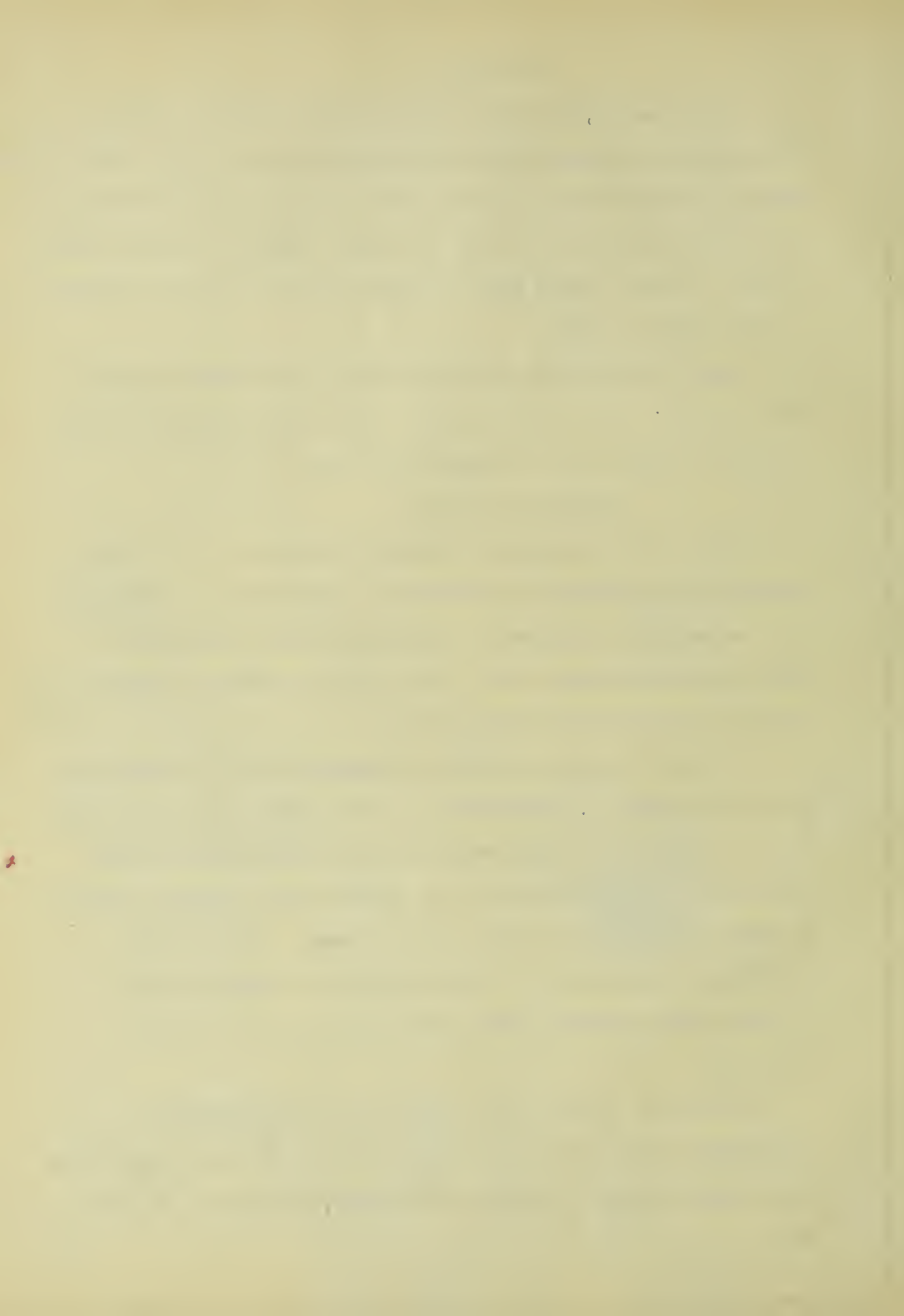
Calculations were made involving the total flux and the probable tooth density and, from these results it was decided to use a line pressure of 6600.

## Number of Poles

Since the voltage and frequency which is to be impressed is determined, a number of motors may be designed . The following preliminary calculations are necessarily rough and approximate, but they will be used as a basis for more accurate determinations.

To begin. with, it will be assumed that the motor is to be connected Y. Reasons for this method of connection and the effect of Y and delta connections will be taken up later. A slot pitch of 1.4 inches and a current density of 1800 amperes per square inch is used. Under these conditions the number of conductors per phase is fixed for any given diameter and, consequently, the flux may be found.

Motors of 4, 6, and 8, poles were designed with diameters ranging from 24 to 72 inches. It was found that, with diameters of less than 48 inches, the length of the



armature was excessive. For any given diameter the volume of iron and copper varied almost directly with the number of poles used and the inductance remained practically constant. From this it is seen that for a minimum iron and copper cost the number of poles should be as small as possible. With two poles an even flux distribution is not possible and the torque is not evenly balanced. For this reason four poles were assumed.

#### Diameter.

For any given number of poles in the above machine, the reactance was found to vary inversely with the diameter, while the iron and copper cost remain the same. A maximum should therefore be used and this will be determined by the maximum allowable peripheral speed. For a 25 cycle 4 pole machine the synchronous speed is 750 R. P. M. With a squirrel cage rotor and closed slots a peripheral speed of 12000 feet per minute is allowable. Therefore the diameter is,

$$D = \frac{12000}{\pi \times 750} = 5 \text{ feet (nearly)}$$

#### Length of Air Gap.

The length of the air gap has a very important bearing on the design of an induction motor. With any given flux density, the ampere turns for the air gap varies directly with its length. With an open slot, the inductance will vary inversely with the length of the gap, but with a closed slot, such as is used on induction motors, the length of the gap will not affect the inductance to so great



an extent, as will be shown later. It appears then that the gap length should be as small as possible. This minimum length is fixed by the mechanical considerations involved.

The following table shows the width of gap used in a number of machines in service .

H. P.	185	220	400	500	1650
Diam (in)	51.2	43.0	96.0	118	199
Lt. A.C.	.049	.063	.108	.069	.157
Perp. Sp.	10100	5630	3150	3090	6530

The variance of these results illustrate the difference of opinion held by designers in regard to this point. For a motor of 5000 K.W. and high peripheral speed, the length of gap should be at least .07 or .08 inch. For safety this value was increased to .1 inch for this machine.

#### Number of Conductors per Slot.

The above calculations of , voltage, frequency, number of poles, and diameter are comparatively simple. They are either determined by previous designs or by a consideration of one variable.

To decide upon the number of conductors per slot, and the number of slots per pole per phase, more elaborate calculations are necessary. There is a very close relation between these two variables. The final values selected will depend upon the method of connecting the machine, the flux densities used, the maximum allowable inductance, and the magnetizing current.

It will be shown later that the inductance per phase



is given by the equation,

$$L = 3.2N^2(Gxl + G'xl') \times S \times k \times 10^{-8}$$

N = Number of conductors per slot

S = Number of slots per pole per phase

k is a design constant depending on the number of slots per pole per phase.

The quantity G is a constant depending upon the shape and the size of the slot, and the length of the air gap. Its value varies from about 3 for wide open slots to 8 for partially closed slots. It is proportional to the permeability of the path per inch of imbedded conductor. Then the total permeability of one slot is equal to Gxl where l is the length of the armature. Assuming that the reluctance of the end turns is ten times that of the slot,  $G' = .1G$  and the total permeability of one end turn is  $G'xl'$  where  $l'$  = the length. For any given diameter and length of armature, this value of  $Gxl + G'xl'$  is determined by the shape of the slot and the length of the air gap. However, the length of the armature is determined by the value of flux used, which depends upon the number of turns per phase.

From these interrelations it is evident that no very simple method can be obtained to determine the value of N or S. Since N occurs in the formula as a second power, its limiting value may be approximately determined.

Thus assuming G to be about 4 and l to be 20  $Gxl = 80$ . By the method used in the final calculations,  $l'$  is found 56.5 inches for a diameter of 60 inches, then



$Gx1 + G'x1' = 106.6$ . Assuming 1.5 inches as the slot pitch, the number of slots per phase is 40 and  $k = 2$ . Taking the maximum  $I_x$  drop as 15%,

$$\text{Then } L = \frac{E_x \cdot 15}{I_x 2\pi \times f} = \frac{3820 \times 15}{436 \times 2\pi \times 25} = .00835 \text{ henrys.}$$

$$.00835 = N^2 \times 3.2 \times 40 \times 2 \times 106.6 \times 10^{-8}$$

$$N = 6 \text{ (about)}$$

Motors were designed with 1, 2, and 3 turns per slot and with 6 to 18 slots per pole per phase. The results of these designs are given in the following table.

Slots/p/p.	Flux	Wd. of Slot.	Depth	$I_x\%$	Lt. of Arm.
(One turn per slot)					
10	86.0	.942	1.182	7.18	41.4
12	71.6	.785	1.473	3.75	34.4
14	61.4	.672	1.830	6.10	29.6
16	53.7	.588	2.020	6.20	25.7
18	45.2	.523	2.560	6.47	21.6
(Two turns per slot)					
10	43.0	.942	2.68	10.00	28.3
12	38.5	.785	3.48	12.00	25.1
14	33.7	.672	4.54	14.00	22.3
16	26.9	.588	6.00	20.00	17.9
(Three turns per slot)					
10	28.6	.942	3.07	20.00	20.0
12	23.8	.785	3.95	-----	----
14	20.5	.672	5.02	-----	----

No values for slots per pole per phase of less than



10 are given since the slot pitch for these values is less than 1.5 inches. The calculations for one turn per slot will be first considered. For slots per pole per phase below 14, the length of the armature is too great. For slots per pole per phase 16 and 18 the ratio of the width to the depth of the slot is about 1 to 3.4 and 1 to 4.9 respectively. In a well designed machine this ratio should be about 1 to 3.

Two turns per slot and 12 slots per pole per phase will give a machine of about the right constants and proportions. However, the value of inductance is high and the depth of the slot is too great.

It is clearly evident that three turns per slot cannot be considered because of the inductance and also on account of the depth of the slot.

Therefore, the only machines which can be considered are those with one turn per slot and 16 or 18 slots per pole per phase or 1 with 2 turns per slot and 12 slots per pole per phase.

In order to ascertain more fully the advantages of these two machines, estimates of the cost, maximum output, reactance and magnetizing current must be made.

A consideration of costs involves the question of fractional pitch winding. This will be discussed in the following paragraph.

#### Fractional Pitch Winding

If the stator winding, instead of covering an exact pole



pitch, covers only .5 of the pitch, the winding is said to be .5 pitch. By this method of winding, the length of the end connections is reduced and the inductance is decreased.

Considerable confusion exists among the various text books regarding the meaning of the term fractional pitch. This term is used by some writers in reference to the fraction of the pole pitch chord, and others assume that the fraction of the pole arc is meant. The latter definition is the one used in the following discussion.

Let AB be the pole pitch of a four pole induction motor. The flux is distributed equally over this arc or the total flux is proportional to the chord AB. If the stator wind-

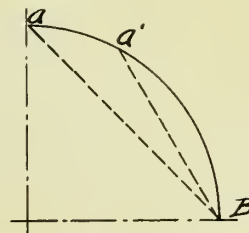


Figure 1.

ing is placed in such a manner that it does not include AB, that is, if fractional pitch is used, then the flux included in the coil is equal to,  $\phi \frac{A'B}{AB}$ . But the coil must include  $\phi$ . Therefore the total flux necessary is,

$$\phi_t = \phi \frac{AB}{A'B}$$

In order to allow this increased flux to pass, the length of the armature is increased and consequently the volume of iron in the machine will be larger.

In this motor the increased iron cost completely overbalances the copper saving, and the slot inductance is almost as large as the decrease in the inductance of the end turns.



While practical considerations eliminate the question of fractional pitch from the calculations for this motor, still it is interesting to note the effect of fractional pitch on the inductance and the costs of copper and iron. On page 55 curves have been plotted showing the variation of these quantities with the winding pitch. These were computed for a motor having 2 turns per slot and 8 slots per pole per phase.

#### Method of Connection

In the above calculations it was assumed that the stator should be connected in Y. The effect of delta connection will now be taken up. If the machine is delta connected the voltage per phase is 6600 volts and the current is 253 amperes. In this case the total flux is increased in the ratio of 6600 to 3820 and the conductor is decreased as 436 is to 253.

In order to obtain the same value of flux the number of turns in series must be increased in the ratio of 6600 to 3820. For the machine of 1 turn per slot and 16 slots per pole per phase the turns in series are 64. For a delta connection this is increased to 110. This may be done either by using by using two turns per slot or by increasing the number of slots per pole per phase.

If two turns per slot is used the area of the copper in the slot is .546 square inches. For delta connection, the machine must be insulated for the line pressure of 6600 volts. This increases the thickness of insulation



to about .12 inches . The number of slots per pole per phase is 14. The slot pitch is 1.347 inches.

If the same width of tooth is used in both machines the flux densities will be almost the same, since the total flux is the same. To be exact, the flux density in the teeth would be greater because the number of slots per pole per phase is less. However, the density may be assumed to be equal and the magnetizing currents will be the same.

It is to be noted that , although the numerical values of these currents are the same, when expressed in terms of the energy current, the percent magnetizing current is larger for delta connection. For example, if the magnetizing current for Y connection is 20%, then for delta connection it would be  $20 \times \sqrt{3}$  or 34.6%.

With such heavy insulation the current density would probably be reduced to about 1800 amperes per square inch to allow the heat from  $I^2R$  losses to be radiated. This gives a depth of slot of only 1.6 inches. Such a slot would have a very high inductance but the increase in voltage compensates for this. It is probable that the  $I_x$  drop in per cent would be nearly equal in the two machines. If this condition is assumed, then the power factor would be much smaller for delta connection due to the high per cent magnetizing current .

The principal advantage of Y connection over delta is, that in case of an accidental ground of one phase



with Y connection, the potential across the insulation is not changed. On the other hand with delta connection, if one phase becomes accidentally grounded, the entire line voltage is thrown across the insulation. For a high voltage this would be very dangerous, since any defects in the insulation with delta connection would remain unnoticed unless a ground occurred. Y connection was therefore chosen. The copper cost is less and the other quantities seem to balance better.

#### Final Determination.

To finally determine which of the two machines above mentioned should be selected, an examination of the costs, reactance, and magnetizing currents must be made. Two motors were designed, one with 2 turns per slot and 11 slots per pole per phase and the other with 16 slots per pole per phase and one turn per slot. These machines will be designated as A and B respectively. The results were as follows.

Machine.	A	B
Cost of Stator Iron	\$805.00	\$1100.00
Cost of Copper	768.00	409.00
Total Cost	\$1573.00	\$1509.00
Percent Reactance	14.60	9.05
A. T. for Air Gap	1820	2050
Percent Mag. Current	8.93	13.80

These quantities give a very good general idea of the characteristics of the two machines. There is very



little choice between the two in regard to first cost. As should be expected the percent reactance of machine A is considerably higher than of machine B. It is of interest to note that while the ampere turns for the air gap of machine A is about 89% of B, the magnetizing current is only 65% of B. This is due to the low air gap density and increased number of turns on A.

It would appear that either of these motors would satisfy the conditions of the problem. The close agreement of the costs of the two machines, whose constants are radically different, seems to indicate a minimum cost. Roughly speaking, the increased inductance of machine A is about compensated for by its low magnetizing current which tends to make the power factor of the two motors about the same.

A consideration of the mechanical features involved seems to be the only <sup>way</sup> <sub>^</sub> to arrive at a decision between these two machines. The slot of machine B is closed to within .2 of an inch, while on A the slot is open .625 of an inch. Taking up the question of heating, it is seen at once that the heat of the conductors will be radiated much faster from B, since the copper area is less and there is on B about .67 of the insulation, which is necessary for A. By considering the difficulty of winding the two, the choice would probably be with B. since the number of turns is less.



In the design of induction motors a very important item is the ampere conductors per inch of periphery.

This is found for B to be,

$$\frac{436 \times 2 \times 12 \times 16}{188.5} = 890$$

And for A

$$\frac{436 \times 4 \times 12 \times 11}{188.5} = 1225$$

This value for amotor of this size should be about 900 or 1000 per inch.

Taking all of these facts into consideration machine B was selected for final design. Methods of design and calculations will now be discussed.



### FINAL CALCULATIONS.

Having determined the principal constants of this machine the actual design will now be taken up. The values which have been determined so far are as follows. 5000 K. W., 6600 volts, 25 cycles, 750 R. P. M., 4 poles, Y connection, 2 conductors per slot, 16 slots per pole per phase, and 60 inches diameter.

In all three phase designs, for simplicity, quantities are taken per phase. In this case the power per phase is  $5000/3 = 1666$  K. W. With Y connection the voltage per phase is  $E/3 = 6600/\sqrt{3} = 3820$  volts.

The current in each winding is then,

$$\frac{1666000}{3820} = 436 \text{ amperes.}$$

The circumference of the stator is,

$$\pi 60 = 188.5 \text{ inches}$$

The total slots are,

$$16 \times 3 \times 4 = 192 \text{ slots}$$

Then the slot pitch is,

$$188.5/192 = .982 \text{ inches}$$

With only two conductors per slot and a high peripheral speed, a high current density may be used. For alternators the current density ranges from 1200 to 1700 amperes per sq. in. In this case the current density taken was 2000 amperes per sq. in.



The area of the conductor is found to be,

$$436/2000 = .218 \text{ sq. in.}$$

At this point it is well to find the probable value of flux required. This is given by the transformer equation,

$$E = 4.44 \times f \times n \times \phi \times 10^{-8}$$

E is the emf per phase.

f is the frequency in cycles per second.

n is the number of turns per phase.

Substituting,

$$\phi = \frac{3820 \times 10^8}{4.44 \times 25 \times 64} = 53.6 \text{ megolines.}$$

The slot should now be laid out, the amount of insulation determined, etc. The correct proportioning of the slot is a very important item and calls for the exercise of good engineering judgement, since its dimensions will in a measure determine the qualities of the motor.

In general, the slot should be so designed that the following conditions are fulfilled.

1. The flux density in the teeth must not exceed 110000 lines per sq. in.
2. The slot inductance must not be too high.
3. The density in the air gap must be a minimum value.
4. The ratio of the height to the width of the slot must be between 3 and 4.

In the design of the slot considerable benefit may be derived from a study of previous designs. The



question of insulation should first be considered. The thickness of insulation is principally determined by the mechanical strains to which the conductor is subjected, insulation for voltage being a minor consideration. This is brought out by an examination of the disruptive strength of various materials. Thompson gives the dielectric strength of oiled canvas as 278 volts per mil thickness, and of mica as 500 volts per mil. For fibre the dielectric strength per mil is about 150 volts. This gives a thickness of  $3820/150 = .0261$  inches for voltage alone.

In considering the thickness for mechanical strength it is well to find the drag on the conductors in pounds. Foster gives for this the formula,

$$P = \frac{B \times l \times I}{11302306}$$

P is the total pull on the conductors in pounds.

I is the current in the conductors in amperes.

B is the flux density in the air gap.

l is the length of the armature in inches.

For this machine the pull per inch of conductor is, assuming  $B = 70000$ ,

$$p = \frac{70000 \times 436}{11302306} = 70 \text{ pounds.}$$

For 550 volt machines Hobart gives a total thickness of slot insulation as about .036 in. For the same voltage Thompson recommends .06 as a safe thickness. Foster gives



the thickness as .045 in. for a 500 volt machine. The General Electric Co. uses a thickness of from .062 to .125 inches for any voltage.

The wide variation of these results shows the difference of opinion which exists in this matter. In practice the thickness is generally determined by the judgement of the designer or by the rules of the company building the machine. For this particular machine a value of .08 in. was recommended by Dr. E. J. Berg.

The dimensions of the slot are generally obtained by cut and try methods. With only two conductors per slot the best arrangement is to place them side by side in the slot. Then the width of the slot taken up by the insulation is  $2(.08 + .04) + 4 \times .01 = .24$  in. Assuming that the conductor should be 1 inch deep its thickness is .218 in., and the total width of the slot is  $.436 + .24 = .676$  in.

This gives the width of the tooth as .306 in., or with this value the slot is twice as wide as the tooth.

Evidently the depth of the conductor must be increased.

The dimensions of the conductor finally decided upon were .136 x 1.6. This gives a slot width of .512 and the width of the tooth is .47 in. The thickness of the wedge used to hold the conductors in the slot is .2 in. Then the total depth of the slot is  $1.6 + 2 \times .08 + .2 + 2 \times .01 + .005 = 1.985$ . In order that the air gap density be as low as possible, induction motor slots are almost entirely closed up.



It must be remembered in this particular that closing the slot materially increases its inductance and care should be taken that this does not exceed an allowable value.

However in this machine the inductance is very low and the opening in the slot need be made only wide enough for the conductor to pass through. The width of this opening was made .2 in. These dimensions are shown in the drawing on page .

Having found the width of the tooth, the length of the armature may be calculated. Assuming a density of 115000 in the teeth the area required is  $53.6/115000$  or 466 sq. in. There are 16x3 teeth per pole. Therefore the length of the armature is,

$$466/48 \times .47 = 21 \text{ in. (about)}$$

Due to the widening out of the tooth at the bottom, the mean density will be less than the value of 115000 assumed at the top. More accurate values of densities will be taken up in connection with the magnetic calculations.

The inductance of the slot may now be worked out from its dimensions.. The slot inductance is the leakage of the

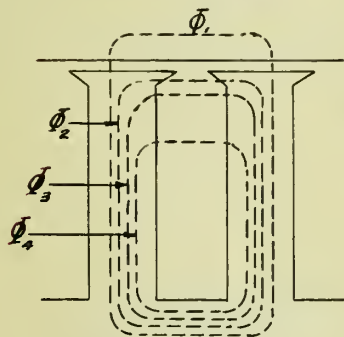


Figure 2. magnetic flux around the conductor. Referring to the figure, this total  $\phi$  may conveniently be divided into four parts.  $\phi_1$  which passes through the air gap and around the conductor.  $\phi_2$  passing from tooth to tooth at the smallest distance.  $\phi_3$  which passes around



the conductor through the insulation.  $\phi_4$  passing through the conductor itself.

These values may be found from a consideration of the reluctance and the m.m.f. of the path around the conductors. It is easily proven for any air cored coil of  $n$  turns and with  $I$  current flowing that,

$$\phi = \frac{4\pi n I a}{10 l}$$

$a$  is the area of the flux in sq. cm.

$l$  is the length of the path in cm.

If  $a$  is expressed in sq. in. and  $l$  in in. then this equation reduces to,

$$\phi = \frac{3.2 n I a'}{l'}$$

In this formula  $a'$  is the area of the flux path, and  $l'$  is the length of the path through air. For a density of 100000 the value of  $\mu$  for armature stampings is 500, or the permeability of the path in iron is 500 times that of air. It is seen then that no appreciable error is introduced if the path through the iron is neglected entirely. Then the length  $l'$  may be taken as the length of the air gap in each magnetic circuit.

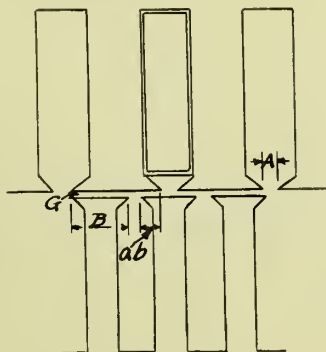


Figure 3a.

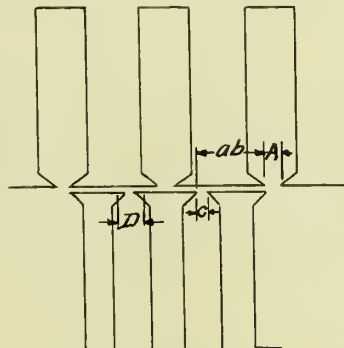


Figure 3b.



The value of  $\phi_1$  will first be considered. Fig. 2a shows one position which the rotor might assume. Here the area ab of the flux is the minimum area. In this case the flux will follow the path indicated and  $l'$  will be  $2G$ ,  $ab = (B - A)/2$ . Then  $\phi_1$  for position A is,

$$\phi_{1a} = 3.2 F \frac{B - A}{4G}$$

F is the m. m. f. =  $nI$

In fig 2b another position of the rotor is shown. Here the area ab of the flux is a maximum. In this case the flux will pass through the air gap twice, and will probably cross through the wedge in the rotor slots.

From the fig  $ab = B + (C - A)/2 = a'$ , and  $l' = 2G + D$

Then  $\phi_1$  for this position is,

$$\phi_{1b} = 3.2 F \frac{2B + C - A}{2(2G + D)}$$

The average value of these two results should be taken as  $\phi_1$  or,

$$\phi_1 = 3.2 F \left( \frac{B - A}{8G} + \frac{2B + C - A}{4(2G + D)} \right)$$

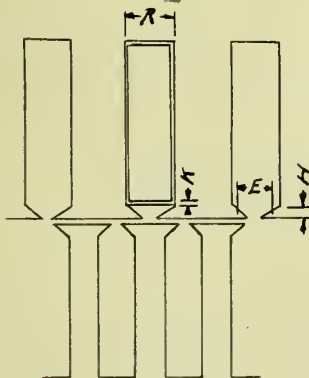


Figure 4.

From fig 4 it is seen that

$l'_2$  is E and  $a'_2$  is H then,

$$\phi_2 = \frac{3.2 F H}{E}$$

Also  $l'_3$  is R and  $a'_3$  is K then,

$$\phi_3 = 3.2 F \frac{K}{R}$$

If uniform current distribut-

ion is assumed in the conductor,

at any distance x, fig. 5 the current  $I_x = I \frac{x}{S}$ , and  $F_x$  is

$$NI_x = I \frac{x}{S} N = F \frac{x}{S}$$



Now  $l' = R$ . Let  $d\phi$  = the flux passing through the area  $dx$ .

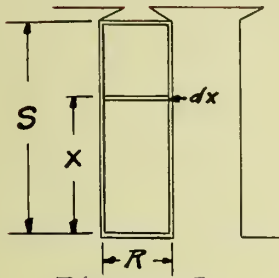


Figure 5.

The m. m. f. for this flux is  $F \frac{x}{S}$ .

This flux will cut  $\frac{x}{S}$  of the total conductors in the slot. Then the equivalent flux  $d\phi$ , which may be assumed as cutting all the conductors is,

$$d\phi = \frac{3.2 F}{R} \frac{x^2}{S^2} dx$$

The total equivalent flux is  $\int d\phi$  or,

$$\phi_4 = \frac{3.2 F}{R S^2} \int_0^S x^2 dx = \frac{3.2 F S}{3 R}$$

Now the total leakage flux is,

$$\phi = \phi_1 + \phi_2 + \phi_3 + \phi_4$$

Substituting,

$$\phi = 3.2 F \left( \frac{B-A}{8 G} + \frac{2B+C-A}{4(2G+D)} + \frac{H}{E} + \frac{K}{R} + \frac{S}{3 R} \right)$$

$$\phi = 3.2 F G = 3.2 N I G$$

where,

$$G = \left( \frac{B-A}{8 G} + \frac{2B+C-A}{4(2G+D)} + \frac{H}{E} + \frac{K}{R} + \frac{S}{3 R} \right).$$

and is constant for any given slot. The self inductance in absolute units is,  $L = \phi N / i$ , and  $L$  in henrys is,

$$L = \frac{\phi N 10^{-8}}{I}$$

where  $I$  is in amperes.

Substituting the value of  $\phi$ ,

$$L = \frac{3.2 N G N \cancel{I} 10^{-8}}{\cancel{I}} = 3.2 N^2 G 10^{-8} \text{ henrys,}$$

for one slot and unit length of armature.



For  $S$  slots per phase , and  $l$  length of armature, the inductance per phase is,

$$L = 3.2 N^2 G' S l k 10^{-8}$$

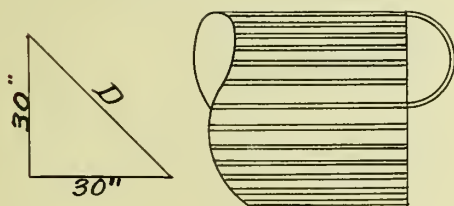
where  $k$  is a design constant depending upon the number of slots per pole per phase .

For 1 slot per pole per phase ,  $k = 1$ , for 16 slots per pole per phase  $k = 2.6$ . The formula neglects the inductance of the end turns. Assuming that the value of  $G$  for the end turns =  $G' = .1 G$ , and the length of the end turn =  $l'$  the total inductance per phase is,

$$L = 3.2 N^2 (G l + G' l') S k 10^{-8}$$

The effective length of the armature has been found to be 21 in. Allowing 10% for laminations and putting in 5 ventilating ducts .44in. wide the gross length of the armature is found to be 25.53 in.

The length of the end turn must now be found. The method of winding the armature will determine this length. A close enough approximate value is obtained by consider-



ing the end turn to lie in a half circle whose diameter is the pole pitch chord. Then for a four pole machine this diameter is,

Figure 6.

$$D = \sqrt{2} R = \sqrt{2} \times 30, \text{ and}$$

the length of the end turn is,  $\pi \sqrt{2} \times 30 / 2 = 66.5 \text{ in.}$

From the drawing on page the values of  $A, B, C$ , etc., in the formula for  $G$  are as follows;  $A = .2, B = .632, C = .1, D = .21, E = .356, G = .1, H = .2, K = .09,$



$R = .512$ ,  $S = 1.6$ . Substituting these values,

$$G = \frac{.632 - .2}{.3} + \frac{1.264 + .1 - .2}{4(.2 + .21)} + \frac{.2}{.356} + \frac{.09}{.512} + \frac{1.6}{.512 \times 3}$$

$$G = 3.0270. \quad G' = .3027$$

Then,  $L = 3.2 \times 4 \times (3.027 \times 25.53 + .3027 \times 65.5) \times 64 \times 2.6$

$$L = .00207 \text{ henrys.}$$

The reactance of self inductance in ohms is

$$x_0 = 2\pi f L = 2\pi \times 25 \times .00207 = .3260 \text{ ohms.}$$

The reactance drop in percent of the voltage per phase is,

$$I_x = \frac{436 \times .326}{3820} = 3.72\%$$

The question of the resistance of the stator is next taken up. The length of one turn is  $66.5 \times 2 + 25.5 \times 2 = 184 \text{ in.}$  The total length of conductor is  $184 \times 16 \times 4 = 11780 \text{ in.}$  or 981 ft. The area of the conductor is .218 sq. in. The resistance of the conductor per foot at  $50^\circ \text{ F.}$  is .0000419 ohms. then the total resistance of the stator per phase is  $981 \times .0000419 = .0411 \text{ ohms.}$



## ROTOR.

The rotor is relatively of little importance in determining the performance of the machine. The number of slots in the rotor is generally made greater than those on the stator. In order to avoid dead points in starting, the number of rotor slots are made prime to those of the stator. This insures smooth running and starting. For 16 slots per pole per phase Foster gives the number of rotor slots as 20 per pole per phase. However the exact number is immaterial, and the value which gives the best slot dimensions and flux densities in the tooth will be taken. For this motor, the number is  $4/3$  stator slots + 1. This gives 257 as the total number.

The winding consists only of large copper bars completely filling the slots, which are short circuited at both ends.

The current in the rotor bars is obtained from the ratio between the stator and rotor conductors in exactly the same manner as in a transformer.

Then the rotor I is,

$$I_r = \frac{2 \times 192 \times 436}{257} = 650 \text{ amperes.}$$

Since no insulation is placed on these conductors, the current density may be increased to 2100 amperes per sq. in. giving an area of  $650 / 2100 = .309$  sq. in.

The slot pitch is  $(30 - .1)2\pi/257 = .732$  in.



Assuming a density of 100000 in the teeth, the area of the exposed iron per pole is 536 sq. in., and the total area is  $4 \times 536 = 2144$  sq. in. The mean width of on tooth is  $2144 / 257 \times 21 = .397$  in., the width of the tooth at the circumference is made .412 in. This makes the width of the slot .320 in., and allowing .02 in. for insulation, the bar will be .3 in. x 1.03 in. The slot depth is then  $1.03 + .02 + .2 = 1.25$ . Since the reactance varies directly as the frequency and , at synchronous speed, the frequency in the rotor is zero, the slot may be almost entirely closed up. The dimensions of this slot are shown on the drawing on page .

In the formula for G, the quantities A, B, C, etc., are as follows; A = .1, B = .782, C = .2, D = .356, E = .21, G = .1, H = .2, K = .01, S = 1.03, R = .32.

$$G = \left( \frac{.782 - .1}{.8} + \frac{1.564 + .2 - .1}{4(.2 + .356)} + \frac{.2}{.21} + \frac{.01}{.32} + \frac{1.03}{3 \times .32} \right)$$

$$G = 3.6580 \quad G' = .3658$$

Then,

$$L = 3.2 \times 1 \times 3.658 \times 25.53 \times 85.7 \times 3.1 \times 10^{-8}$$

$$L = .000792 \text{ henrys.}$$

The reactance of self inductance in ohms is,

$$x_0 = 2\pi f L = 2\pi \times 25 \times .000792 = .1245 \text{ ohms}$$

The reactance drop in percent of the voltage per phase is,

$$I_x = \frac{650 \times .1245}{3820} = 2.12\%$$



The currents in the various parts of the rotor are next figured. Let fig.3 represent the squirrel cage rotor

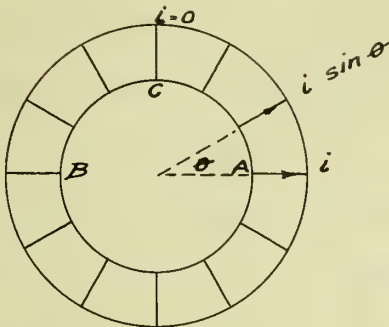


Figure 8.

of a two pole machine, the two circles being the short circuiting rings and the radial lines representing the conductors.

Hobart gives the following discussion. Let  $i$  = the effective current in bar A. Then the

current in any other bar is  $i \sin \theta$ , where  $\theta$  is in electrical degrees. The average current in the bars from A to C

is,

$$\frac{2i}{\pi} \int_0^{90^\circ} \cos \theta \, d\theta = \frac{2i}{\pi} \text{ amperes.}$$

Now if  $Z_1$  is the number of conductors per pair of poles, then the number of conductors from A to C is  $Z_1/2$ . It is seen that the current in the end rings will increase from a  $i/2$  value at A to a maximum value at C. The maximum value of this current is the average current in each bar times the number of bars between A and C or,

$$J = \frac{2 i Z_1}{2 \pi} \text{ amperes.}$$

This is the average value of  $J$  per pair of poles or,

$$j = \frac{iZ}{2\pi} \text{ amperes.} \quad \text{If } Z_1 = Z/2$$

The average current in each bar from the above equation is  $650 \times 2 / \pi = 414$  amperes.

The average value of the current in the end ring is,

$$j = \frac{414 \times 85.7}{2 \pi} = 5650 \text{ amperes.}$$



Since the end ring is open to the air , a density of 2500 amperes may be used. This gives an area of 2.25 sq.in. The resistance of this bar is .00000406 ohms per foot. Assuming that the mean radius is 29 in., the total resistance of both rings is, .0001234 ohms. This ring will be made out of brass. Since the resistance of brass is three times that of copper the resistance of the two rings per phase if made of brass is .0001234

The total resistance of the rotor must now be expressed in terms of the primary resistance. This may be done by a consideration of the  $I^2R$  losses in the two parts of the rotor circuit. The  $I^2R$  loss in all the bars on the rotor per phase is,

$$650^2 \times .0000628 \times 85.7 = 2272 \text{ watts.}$$

The  $I^2R$  loss in the rings per phase is,

$$5620^2 \times .0001234 = 3940 \text{ watts.}$$

The total  $I^2R$  loss is,

$$2272 + 3942 = 6214 \text{ watts}$$

The equivalent resistance of the rotor in stator ohms is,

$$6214 / 436^2 = .03265 \text{ ohms.}$$

The reactance of the rotor may be reduced to stator ohms by the square of the number of conductors or,

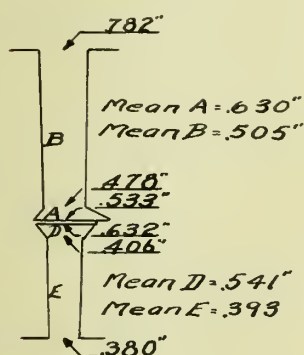
$$x_1 = \frac{384 \times .1245}{257} = .2785 \text{ ohms.}$$



# MAGNETIC CALCULATIONS.

The calculations of the flux densities to use, the length of the magnetic path, and the magnetizing current will next be taken up.

The flux density in the teeth has already been determined. The total flux per pole is 53.6 megolines. There are 48 teeth per pole on the stator. Assuming that the flux is evenly distributed, the flux in each tooth is 1.117 megolines. The mean density in part A and B fig. 7 is



determined by the mean width of the

$$\begin{aligned} \text{tooth or, } B_a &= \frac{1117000}{21 \times .63} = 84500 \text{ lines per sq.in.} \\ B_b &= \frac{1117000}{21 \times .5055} = 105000 \text{ lines per sq.in.} \end{aligned}$$

The flux in the stator body divides or the stator flux is

$$\text{Figure 7. } 53.6/2 = 26.8 \text{ megolines. It must now}$$

be decided what flux density shall be used in this part. At first a density of 80000 was assumed, but on account of the long magnetic path, the ampere turns required for this value were too large. The density finally selected was 70000. The area required is  $26.8/70000 = 383$  sq. in. The thickness of the rotor body is  $383/21 = 18.25$  in.

The flux per tooth of the rotor is  $53.6 \times 4/257 = .834$  megolines. The mean densities referring to fig 7 are,



$$B_d = \frac{834000}{21 \times .3415} = 73400 \text{ lines per sq. in.}$$

$$B_e = \frac{834000}{21 \times .393} = 101000 \text{ lines per sq. in.}$$

The total flux in the rotor body will be the same as for the stator ,or 26.8 megolines. The magnetic path here is much shorter than in the stator , so the density may be assumed as 80000. This gives an area of  $26.8/80000 = 335$  sq. in. The thickness of the rotor body is then  $335/21 = 15.95$  or 16 in.

The area of the flux in the air gap must now be determined. A close approximation of this is obtained, if it is taken as the mean between the area of the exposed iron on the rotor and stator teeth. The area of the exposed iron on the stator per pole is,

$$48 \times 21 \times .782 = 789 \text{ sq. in.}$$

and on the rotor

$$65.75 \times 21 \times .632 = 1135 \text{ sq.in.}$$

And the mean area is 962 sq. in.

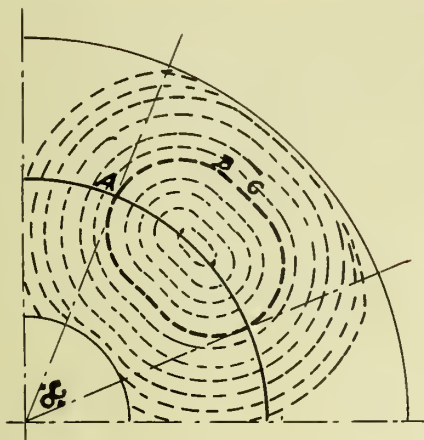
The air gap density is,

$$B_g = \frac{536000}{962} = 55750 \text{ lines per sq. in.}$$

Having found the densities in the various parts of the magnetic circuits, the length of the path is next considered. Owing to the uneven distribution of the flux, an accurate determination of this path is not possible. The fig.9 shows how the flux travels. It is seen that



due to the absence of any definite poles the flux will spread throughout the entire yoke. A very accurate



accurate approximation of the equivalent path of the flux is, to take the mean length indicated by the black line shown in fig. 9. The angle  $\alpha$  is taken as  $2\pi/2P$  where  $P$  is the number of poles. In a four pole machine  $\alpha$  is  $45^\circ$ .

Figure 9.

The radius of the curved path ab through the body is taken as one-half the width of the body. The length ab is then  $2 \times 9.125/4 = 14.362$  in. The radius of bc is  $30 + 1.985 + 9.125 = 41.11$  in., and the length bc is  $(2 \times 41.11/16) - 9.12 = 7.00$  in. The total length of path in the stator is  $14.32 + 7.00 = 21.32$  in.

The path in the teeth is equal to the length of the teeth.

The length of the path in the rotor is found in the same way as the length of path in the stator. It is

$$4\pi + (30 - .1 - 8 - 1.25)\pi/4 - 8 = 12.73 \text{ in.}$$

From the diagram it is seen that the flux per pole divides forming two paths in parallel, or the m. m. f. forcing the flux through the entire length of the path is twice the m. m. f. of a single pole. Hence, since the flux has been taken per pole only one half the total



length of the path should be taken.

The total ampere turns per pole may now be found. The various lengths of the magnetic circuit have been lettered as shown in fig 10. The densities, ampere turns per inch, and total ampere turns for each part of the circuit are tabulated in the following table.

The B & H curve used is found on page .

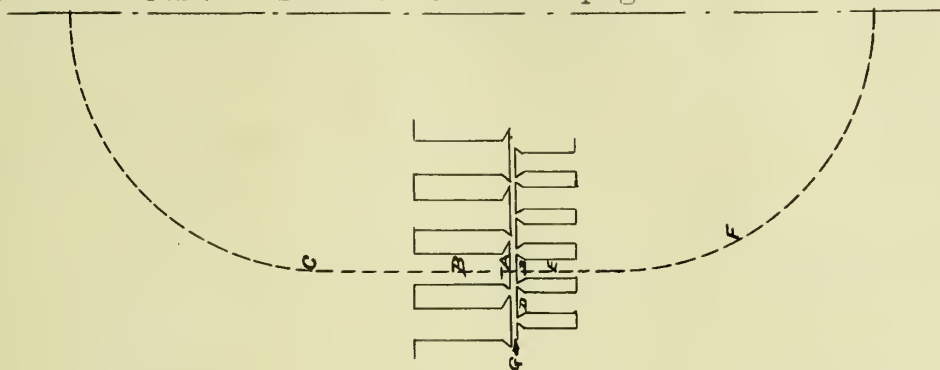


Figure 10.

Part.	Density	A. T./ in.	Length.	Total A. T.
A	84500	30.0	.20	6.0
B	105000	127.5	1.78	227.5
C	70000	14.5	21.32	309.2
D	73400	17.3	.20	3.7
E	101000	92.5	1.05	97.1
F	80000	25.8	12.73	329.0
G	55750 ( A.T. = 55750x.313x.1.)			<u>1742.0</u>

Total ampere turns = 2714.5

The m. m. f. of the induction motor is analagous to the armature reactions of an alternator and is found by the same formula. That is,

$$A. T. = 1.5\sqrt{2}xNxI$$



$N$  = the number of turns per pole per phase.

Substituting, .

$$2714.5 = 1.5\sqrt{2} \times 16 \times I$$

$$I_{\text{mag}} = 80.0 \text{ amperes.}$$

Expressed as a percent of the total energy current.

$$I_{\text{mag}} = 80 / 436 = 18.35 \%$$

In order to find the hysteresis and eddy current loss and the cost of the iron the volume of the iron must be calculated. Keeping the same letters for the various parts of the magnetic circuit as was used before, the volumes, hysteresis and eddy current loss, weight, and costs are found in the following table. The weight of the iron was calculated at .2775 lbs. per cu. in. The cost of the iron was taken at 4.5 cents per pound.

Part.	Volume (cu.in.)	Total Wt. (lbs.)	Hyst.&E.C. (per lb.)	Total Hyst. &E.C. loss.	Cost. (dollars)
A	508	141	.67	94	6.3
B	3635	1080	1.09	1178	48.6
C	98800	27400	.45	12350	1233.0
D	584	162	.50	81	7.2
E	2260	627	1.01	633	28.0
F	45450	12600	.59	7430	567.5
Totals				21766	\$1890.00

The total weight of copper on the stator is ,

$$981 \times .218 \times 555 / 144 = 824 \text{ lbs. per phase.} = 2472 \text{ lbs. total}$$

At .16 per lb the cost is 395.50 dollars.

The total weight of copper on the rotor is, *495 lbs.*



The weight of brass on the rotor is ,

$$182 \times 2 \times 2.25 \times .304 = 249 \text{ lbs.}$$

The cost of the copper and brass on the rotor at 13 cents per pound is,

$$( 249 + 495 ) .13 = 119 \text{ dollars}$$

The total cost of the entire machine is ,

$$119 + 395.5 + 1890 = 2304.50 \text{ dollars}$$



## STEINMETZ CALCULATIONS.

There are two general methods of calculating the performance of an induction motor. The circle diagram is a graphical method of finding the various quantities. The most accurate method is by the use of the mathematical calculations deduced by Steinmetz in his "Elements".

These equations are deduced as follows; let  $g$  = the conductance of the primary circuit due to the magnetic power current, and  $jb$  = the susceptance due to the magnetizing current. Then the primary exciting impedance is  $Y = g + jb$ . Let  $e$  = the counter generated e.m.f. of the motor,  $Z_0 = r_0 - jx_0$  = the primary self inductive impedance and  $Z_1 = r_1 - jx_1$  = the secondary self inductive impedance in terms of the primary. If  $s$  = the slip ( where  $s = 1$  denotes zero speed ),  $1 - s$  = the speed of the motor as a fraction of synchronous speed, and  $sf$  = the frequency of the rotor currents. Then at a slip =  $s$  the secondary impedance is ,

$$Z_1^s = r_1 - jsx_1.$$

And the secondary current is,

$$I_1 = \frac{se}{Z_1^s} = \frac{se}{r_1 - jsx_1} = e \left( \frac{sr_1}{r_1^2 + s^2 x_1^2} + j \frac{s^2 x_1}{r_1^2 + s^2 x_1^2} \right) \\ = e ( a_1 + ja_2 )$$

the primary exciting current is,

$$I_{00} = eY = e ( g + jb )$$



and the total primary current is,

$$I_0 = e ((a_1 + g) + j(a_2 + b)) = e(b_1 + jb_2)$$

The primary terminal voltage is the sum of the counter generated e.m.f. and the  $IZ$  drop or,

$$\begin{aligned} E_0 &= e + I_0 Z_0 = e(1 + (b_1 + jb_2)(r_0 - jx_0)) \\ &= e(c_1 + jc_2) = e\sqrt{c_1^2 + c_2^2} \end{aligned}$$

hence the counter generated e.m.f. of the motor is,

$$e = \frac{E_0}{\sqrt{c_1^2 + c_2^2}}$$

Substituting this value in the equation for  $I_0$

$$I_0 = e\sqrt{b_1^2 + b_2^2}$$

The torque of the induction motor is proportional to the product of the generated e.m.f. and the component of the secondary current in quadrature therewith in time and in space. This component is  $ea_1$ . Or the torque is,

$$\text{Torque} = e^2 a_1$$

This value of torque is in its dimensions a power, and it is the power which the torque of the motor would develop at synchronous speed. Then the power developed at the speed of  $(1 - s)$  synchronous speed, or the actual power output of the motor is,

$$P = (1 - s) e^2 a_1.$$

The primary input is the sum of the products of the in phase components of current and voltage, and the wattless components or,

$$P_0 = e^2(b_1 c_1 + b_2 c_2)$$

The volt amperes or apparent input is,

$$P_a = I_0 E_0.$$



The power factor is,

$$P. F. = P_o / E_o I_o$$

Disregarding the friction loss the efficiency is,

$$Eff. = P / P_o$$

And the apparent efficiency is,

$$App. Eff. = P / E_o I_o.$$

The total horse power for a three phase motor is,

$$H. P. = .00403 P$$

The torque in foot pounds is,

$$Torque = 1.41 T / f . \text{ Where } T \text{ is in synchronous watts.}$$

The methods of finding the values of  $x_o$ ,  $x_1$ ,  $r_o$ ,  $r_1$ , has been taken up in the design of the motor.

Since  $g$  is the conductance of the primary circuit due to the magnetic power current or hysteresis loss, if the impedance drop is neglected the value of  $g$  is,

$$g = I_h / E_o , \quad I_h = W_h / E_o \text{ or } g = W_h / E_o^2$$

The magnetic power is composed of the hysteresis loss per phase and the  $I^2 r$  loss in the stator due to the exciting current. This latter loss will be sufficiently accurate if the exciting current is assumed to be equal to the magnetizing current. The magnetic power is then,

$$21766/3 + 80^2 \times .0411 = 8969 \text{ watts per phase.}$$

The hysteresis current is,

$$8969 / 3820 = 2.348 \text{ amperes .}$$

And the value of  $g$  is,

$$g = 2.348 / 3820 = .000615.$$



The magnetizing current has already been found to be 80 amperes . Then ,

$$b = 80.0 / 3820 = .02093$$

By assuming values of the slip the entire performance of the motor may be calculated by means of these equations. The data for these calculations is found on page

These quantities were also worked out for threequarters one half and one quarter normal voltage impressed on the motor. If the B & H curve page 56, and the curve for finding the losses page 57, are assumed to be straight lines these calculations are very much simplified. The flux varies directly as the impressed voltage, and hence the densities and the components of the exciting current will also vary directly with the impressed voltage. Therefore the values of  $g$  and  $b$  will be constant. Since the values of  $r_0$ ,  $x_0$ ,  $r_1$ , and  $x_1$  are also constant the values down to the value of  $e$  may be taken from the normal voltage calculations.



## DESIGN OF SHAFT AND BEARINGS.

In order to figure the diameter of the shaft, the total weight of the rotating element must be known. From the previous rotor calculations, the weight of the laminations are 13389 pounds. The weight of the copper is 651 pounds. The total weight is 14040. The weight of the spider and hub was roughly calculated as 1910. Then the total weight of the rotating element is about 16000 pounds. Merrimans "Mechanics" gives the diameter of the shaft for combined twisting and bending as,

$$d = \sqrt[3]{\frac{16 \sqrt{P_p^2 + M^2}}{S_p \pi}}$$

Where M is the bending moment of the load and Pp is the twisting moment due to the applied forces. When H horse power is transmitted at a speed of N R. P. M.,

$$P_p = 63030 H / N$$

Substituting 6700 for H and 750 for N,

$$pP = 56300 \text{ pound inches.}$$

To figure the bending moment the worst possible conditions are assumed, namely that all the load is concentrated at the center of the shaft. The distance between the bearings is 44 inches. Then,

$$M = .125 \times 16000 \times 44 = 88000 \text{ pound inches.}$$

And ,

$$d = \sqrt[3]{\frac{16 \sqrt{563000^2 + 88000^2}}{5000 \pi}} = 8.34 \text{ inches.}$$



A shaft of 9 inches diameter was used.

In Leutwiler and Duncan's "Notes on Elementary Machine Design", the diameter of the hub is given as

$$D = 1\frac{5}{8} d + \frac{1}{8} \text{ in. where } d \text{ is the bore.}$$

Then the diameter of the hub is,

$$D = 1\frac{5}{8} \times 9 + \frac{1}{8} = 14.75 \text{ in.}$$

#### Bearings.

In a pamphlet issued by the "Machinery Magazine" the following formula is given for calculating the length of the bearing to use ,

$$L = \frac{W}{Pk} \left( n + \frac{K}{D} \right)$$

L = The length of the bearing.

W = The weight upon one bearing.

k = A constant.

The value of the constant k depends upon the kind of oil used and the care taken of the bearing.

Assuming that a good quality of oil will be used the value of k is 1400

P = the maximum safe unit pressure.

D = the diameter of the shaft.

n = the R. P. M.

The value of P for a motor of this size is about 350, Then,

$$L = \frac{8000}{1400 \times 350} \left( 750 + \frac{1400}{9} \right) = 15 \text{ in. (about)}$$



### DISCUSSION.

When the machine is operating at full rated output of 6700 horse power, the current in the line is 450 amperes. The power factor is .96 , the R. P. M. is 747 and the efficiency is 98.6.

It may be also noted that the points of maximum efficiency and power factor come at about twice full load. The motor can be safely operated at 50% above normal rating without excessive heating. For loads above this value there would be danger of burning out the machine.



## FRACTIONAL PITCH.

(2 turns per slot, 8 slots per pole per phase.)

Percent pitch	1.0	.8	.6	.4
Chord (in.)	42.4	35.2	28.1	18.5
Ø megolines	53.7	64.7	81.0	123.0
B in air gap	86900	86900	86900	86900
Gross lt. armature	20.8	25.2	31.4	48.0
G for armature	9.0	9.0	9.0	9.0
G1 + G'1'	211.3	234.7	267.6	370.0
L (henrys)	.00622	.00670	.00735	.01100
Ix percent of E	11.2	12.0	14.2	19.2
Yoke thickness	20.0	20.0	20.0	20.0
Total lt. of cond.	33600	30950	29000	30600

## Volumes.

Copper (cu. in.)	10750	9950	9350	9850
Iron (cu. ft.)	54.7	63.7	82.2	125.0

## Costs in Dollars.

Copper @ 16¢ lb.	554	512	480	505
Iron @ 4.5¢ lb.	1180	1418	1773	2700
Total	1734	1930	2253	3205



## FRACTIONAL PITCH

(One turn per plot, 11 slots per pole per phase.)

Percent pitch	1.0	.8	.6	.4
Chord (in.)	42.4	35.2	28.1	18.5
Ø megolines	85.6	103.3	129.2	196.4
B in air gap	74000	74000	74000	74000
Gross lt. armature	32.4	39.4	49.2	83.0
G for armature	9.3	9.3	9.3	9.3
G1 + G'l'	333	379	452	649
L (henrys)	.00344	.00388	.00463	.00665
Ix percent of E	6.2	7.0	8.3	11.9
Yoke thickness	18.3	18.3	18.3	18.3
Total lt.of cond.	24500	23800	23740	26900

## Volumes.

Copper (cu. in.)	7450	7180	7160	8130
Iron (cu. ft.)	82.9	100.4	140.2	190.2

## Costs in Dollars.

Copper @ 16¢ lb.	392	381	380	431
Iron @ 4.5¢ lb.	1783	2165	2700	4100
Total	2175	2546	3080	4531



## STEINMETZ CALCULATIONS.

Normal Voltage, 3820 Volts per Phase

Slip	$r_1^2 + s^2 x_1^2$	$a_1$	$a_2$	$b_1$	$b_2$
.001	.001066	.0306	.00026	.03121	.02119
.002	.001066	.0613	.00104	.06191	.02197
.003	.001067	.0920	.00234	.09261	.02327
.004	.001067	.1224	.004165	.12353	.02509
.007	.001078	.2132	.01268	.21433	.03361
.010	.001075	.3039	.02581	.30503	.04674
.020	.001099	.5950	.10110	.59613	.12203
.030	.001137	.8615	.21980	.86263	.24073
.050	.001260	1.2940	.55050	1.29510	.57140
.070	.001446	1.5800	.94100	1.58110	.96193
.100	.001838	1.7750	1.51000	1.76110	1.5309
.150	.002800	1.7490	2.23000	1.75010	2.25090
.200	.004148	1.7575	2.67700	1.57610	2.69793
.300	.007998	1.2240	3.12200	1.22510	3.14290
.500	.020318	.8038	3.41400	.80493	3.43490
.700	.038868	.5915	3.49800	.59263	3.51890
1.000	.078068	.4180	3.55400	.41913	3.57490



$b_1^2 + b_2^2$	$c_1$	$c_1$	$c_1^2 + c_2^2$	$e$	$e^2$
.0382	1.00818	-.00947	1.0082	3790	14380000
.0662	1.00970	-.0194	1.0098	3782	14300000
.0958	1.01140	-.0293	1.0118	3779	14270000
.1260	1.01325	-.0392	1.0135	3770	14200000
.2167	1.01975	-.0684	1.0219	3740	13750000
.3083	1.02775	-.0975	1.0303	3710	13750000
.6075	1.06440	-.1892	1.0810	3500	12250000
.8966	1.11372	-.2711	1.1460	3330	11100000
1.4130	1.23940	-.3986	1.3020	2935	8600000
1.8510	1.37850	-.4765	1.4580	2620	6860000
2.3440	1.57190	-.5156	1.6530	2310	5350000
2.8540	1.80565	-.4785	1.8670	2048	4190000
3.1220	1.94424	-.4028	1.9860	1923	3700000
3.3780	2.07325	-.2708	2.0900	1825	3330000
3.5320	2.15306	-.1214	2.1540	1772	3140000
3.5700	2.17032	-.0487	2.1730	1756	3090000
3.6000	2.18222	+.0101	2.1830	1748	3060000



I o	Torque	P	c b + c b 1 1 2 2	P o	Efficiency
145.8	440000	439000	.03179	457000	96.2
252.7	877000	876000	.02657	895000	97.9
366.0	1312000	1308000	.09346	1333000	98.1
481.0	1738000	1730000	.12421	1763000	98.1
810.0	2990000	2987000	.21630	3030000	98.0
1143.0	4180000	4135000	.30890	4250000	97.4
2130.0	7290000	7150000	.61200	7500000	95.3
2980.0	9570000	9300000	.91600	10180000	91.5
4150.0	11120000	10560000	1.37500	11820000	89.4
4850.0	10840000	10070000	1.72200	11820000	84.7
5420.0	9500000	8550000	2.00400	10690000	80.0
5850.0	7300000	6230000	2.08500	8730000	71.4
6010.0	5780000	4580000	1.98000	7320000	62.6
6160.0	4080000	2860000	1.69000	5630000	50.9
6260.0	2520000	1259000	1.31300	4120000	30.6
6260.0	1826000	548000	1.14200	3530000	15.5
6290	1280000	000000	.95000	2910000	00 0



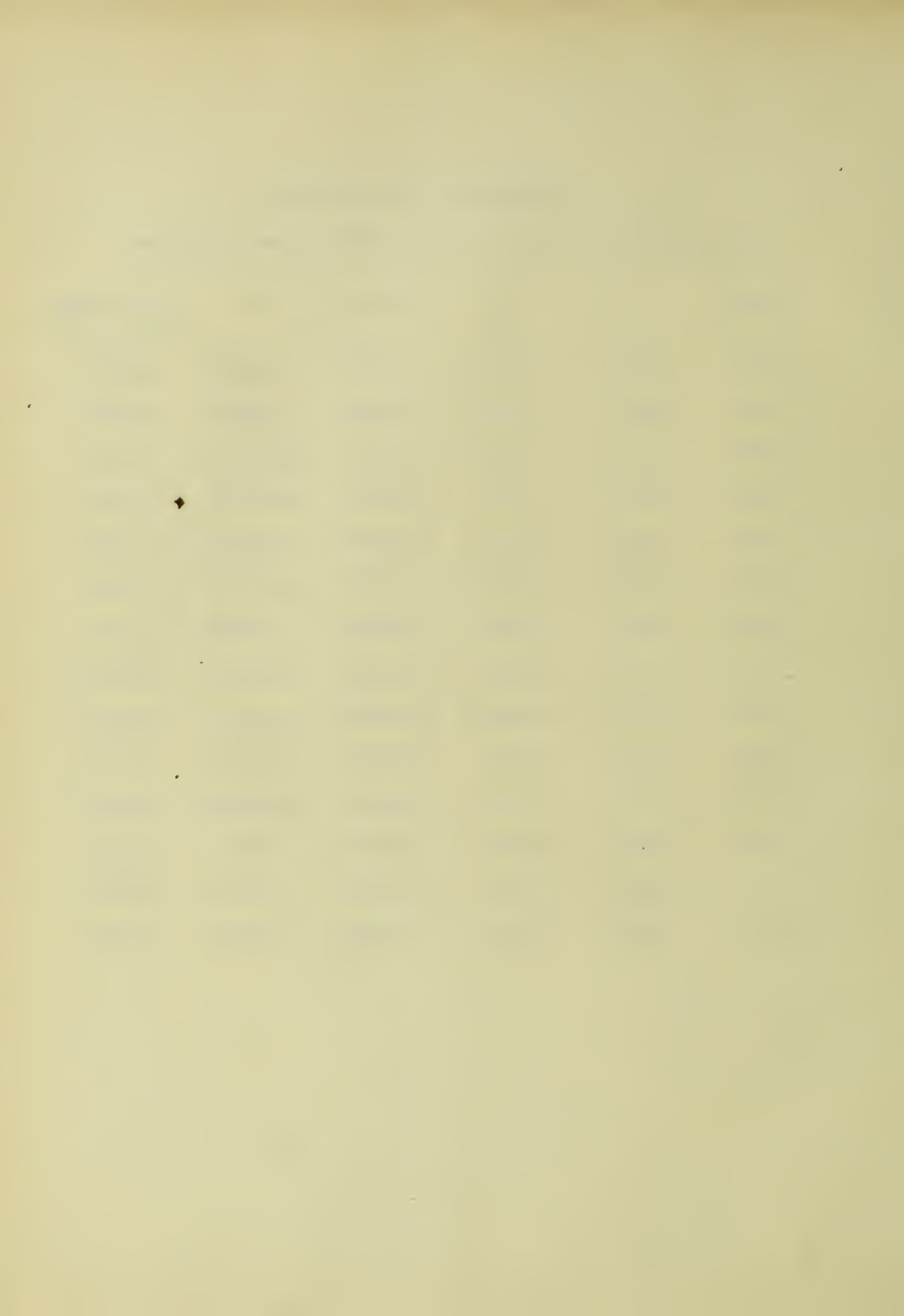
E I o o	P. F.	H. P.	Torque (ft. lbs.)	App. Eff.
557000	.820	1768	25100	78.9
963000	.929	3850	49600	91.0
1397000	.955	5270	74100	93.6
1836000	.961	6970	98100	94.4
3090000	.980	11960	168700	96.1
4370000	.974	16670	236000	94.6
8135000	.922	28800	411500	88.0
11380000	.895	37500	540000	81.6
15850000	.747	42500	600000	66.6
18540000	.638	40400	586000	54.3
20700000	.652	34430	513500	41.3
22350000	.391	25100	396000	27.8
22940000	.320	18450	309500	20.0
23540000	.239	11530	220600	12.2
23900000	.172	5075	136000	5.3
23900000	.148	2210	98600	2.3
24010000	.121	0000	69200	0 0



## STEINMETZ CALCULATIONS.

Three quarters Normal Voltage, 2865volts per phase.

Slip.	e	$I_o$	Torque.	P	$c_1b_1 + c_2b_2$
.001	2840	109.5	247200	246800	.03719
.003	2832	274.5	737500	735500	.09346
.005	2820	441.0	1215000	1208000	.15520
.010	2780	857.0	2350000	2325000	.30890
.020	2650	1610.0	4190000	4110000	.61200
.030	2500	2240.0	5390000	5230000	.91600
.050	2200	3110.0	6280000	5960000	1.37500
.100	1734	4060.0	5340000	4805000	2.00400
.150	1536	4380.0	4130000	3510000	2.08500
.200	1442	4510	3280000	2622000	1.98000
.300	1371	4630.0	2300000	1610000	1.69000
.500	1330	4690.0	1424000	712000	1.31300
.700	1319	4710.0	1028000	308200	1.14200
1.000	1311	4725.0	720000	000000	.95000



P <sub>o</sub>	Efficiency	P. F.	H. P.	Torque ft. lbs.	App. Eff.
257000	96.1	.820	995	13930	78.7
749000	98.2	.953	2963	41600	93.6
1232000	98.1	.977	4875	68500	95.9
2390000	96.3	.975	9375	132500	94.8
4320000	95.0	.938	16550	236500	89.0
5725000	91.4	.892	21070	304000	81.5
6670000	89.3	.748	24000	354000	66.9
6020000	79.8	.519	19350	301000	41.4
4920000	71.4	.392	14130	232800	28.0
4130000	63.5	.320	10570	185000	20.4
3180000	50.7	.240	6490	129700	12.1
2330000	30.6	.174	2870	80500	5.3
1987000	15.5	.147	1242	58000	2.3
1633000	00 0	.121	0000	40600	0 0



## STEINMETZ CALCULATIONS.

One half Normal Voltage, 1910 volts per phase

Slip.	e	$I_o$	Torque.	P	$c_1 b_1 + c_2 b_2$
.001	1893	72.9	109800	109700	.03179
.004	1883	240.5	434500	432500	.12421
.007	1870	405.0	746000	741000	.21630
.020	1768	1065.0	1855000	1818000	.61200
.050	1468	2075.0	2792000	2650000	1.37500
.100	1155	2710	2370000	2132000	2.00400
.150	1023	2925.0	1832000	1557000	2.08500
.200	962	3005.0	1457000	1164000	1.98000
.300	914	3080.0	1023000	716000	1.69000
.500	887	3130.0	632000	316250	1.31300
.700	879	3130.0	449000	134800	1.14200
1.000	875	3145.0	320000	00000	.95000



P o	Efficiency.	P. F.	H. P.	Torque Ft.lbs.	App. Eff.
114000	96.2	.818	443	6300	78.8
441000	98.2	.960	1743	24500	94.1
757000	98.2	.980	2986	42150	95.8
1910000	95.2	.940	7320	104500	89.4
2970000	89.3	.748	10670	157200	66.7
2670000	79.9	.516	8590	133500	41.2
2187000	71.2	.406	6270	103300	28.8
1835000	63.5	.320	4690	82200	20.3
1410000	50.7	.240	2886	57700	12.2
1032000	30.6	.173	1275	35700	5.3
883000	15.0	.147	544	25300	2.3
727000	00 0	.121	000	18050	0 0



## STEINMETZ CALCULATIONS.

One quarter Normal Voltage, 930 volts per Phase.

Slip.	e	$I_o$	Torque.	P	$c_1b_1 + c_2b_2$
.001	949	36.0	27540	27500	.03179
.020	895	537.0	466000	456500	.61200
.050	735	1038.0	699000	664000	1.37500
.100	578	1355.0	595000	535500	2.00400
.150	515	1468	463000	394000	2.08500
.300	457	1543.0	256000	179200	1.69000
.500	444	1567.0	158300	79150	1.31300
.700	440	1570.0	114500	34400	1.14200
1.000	437	1573.0	92100	00000	.95000

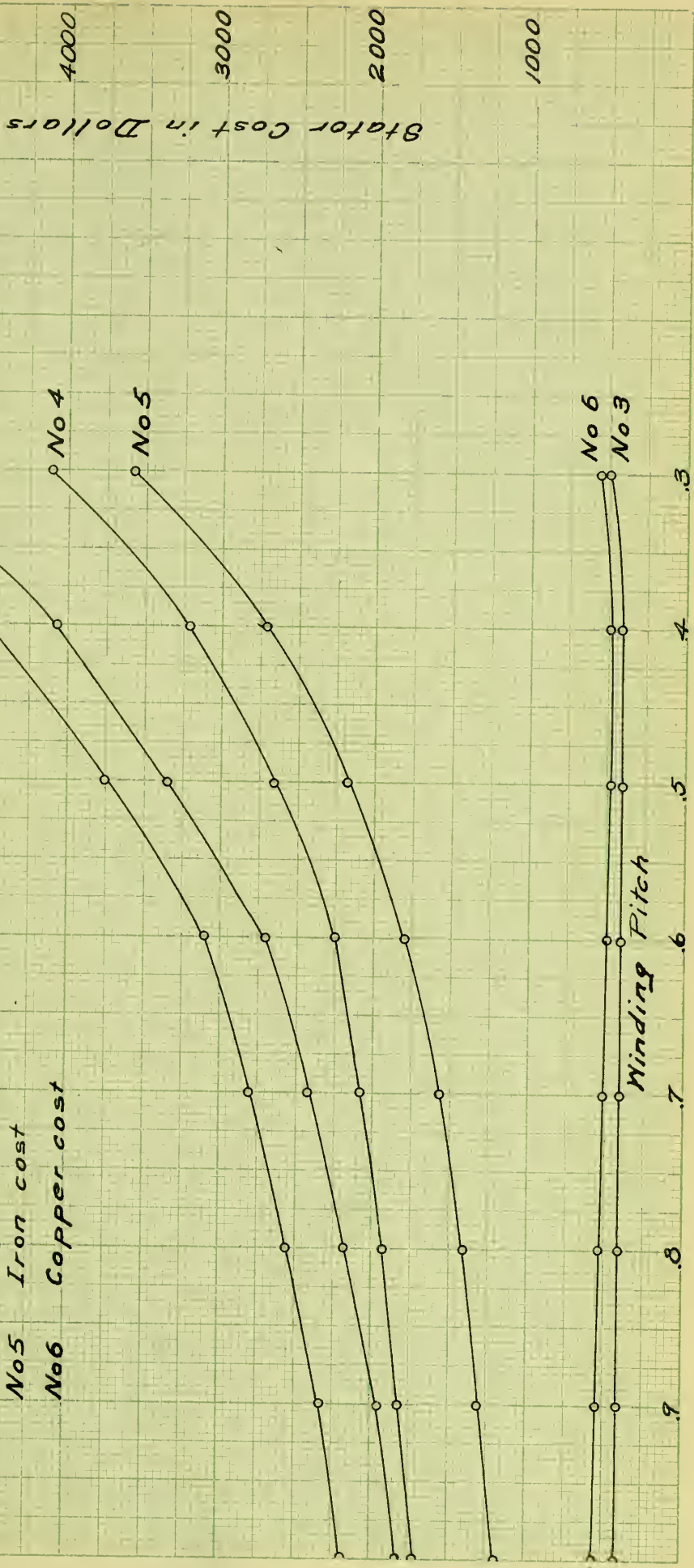


P <sub>o</sub>	Efficiency.	P. F.	H. P.	Torque Ft.lbs.	App. Eff.
28600	96.1	.827	111	1550	79.5
479000	97.1	.935	1800	26280	89.0
743000	89.4	.740	2680	26280	89.0
670000	79.8	.518	2160	33600	41.3
552500	71.3	.395	1590	26100	23.1
353000	50.8	.239	922	14430	12.2
259000	30.6	.173	319	8940	5.3
221500	15.5	.148	139	6460	2.3
182000	00 0	.121	000	5200	0 0

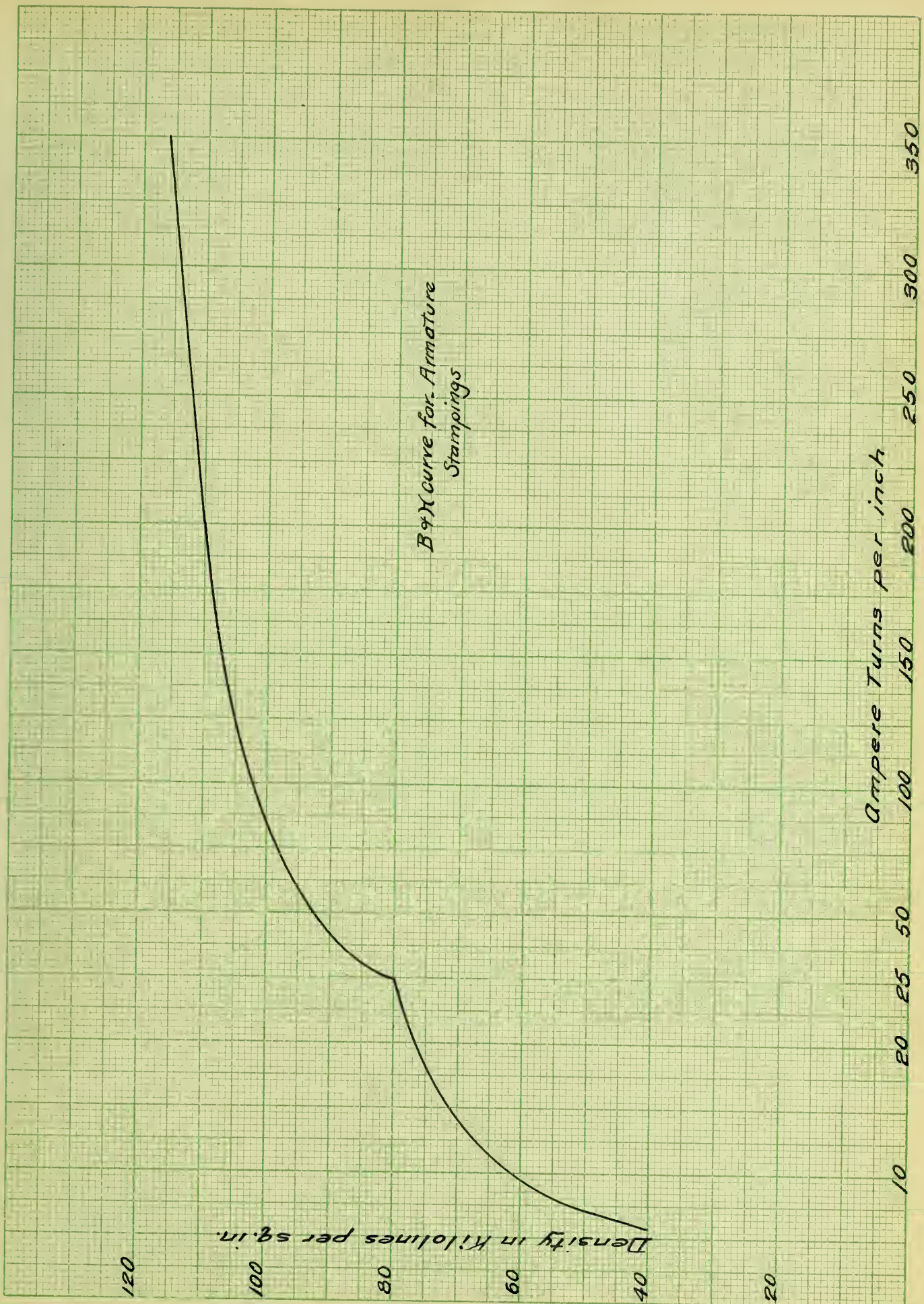


11 Slots per pole per phase  
 1 Turn per slot  
 No.1 Copper and iron cost  
 No.2 Iron cost  
 No.3 Copper cost

8 Slots per pole per phase  
 2 Turns per slot  
 No.4 Copper and iron cost  
 No.5 Iron cost  
 No.6 Copper cost









1.8

1.6

1.4

1.2

1.0

.8

.6

.4

.2

*Hysteresis and Eddy Current  
for Armature Stampings*

Watts lost per pound of iron for 25 cycles

Density in Kilolines per sq. in

20

40

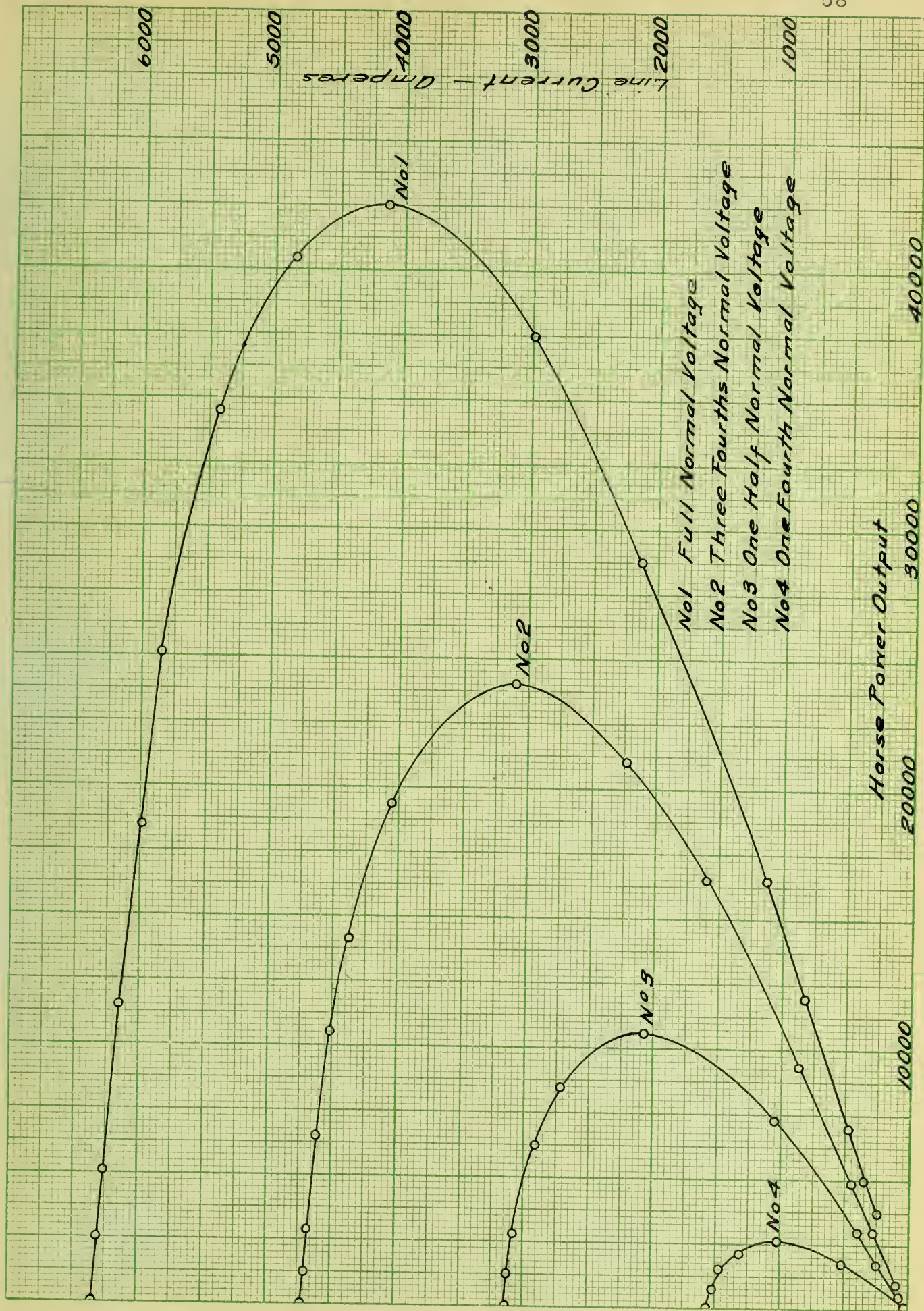
60

80

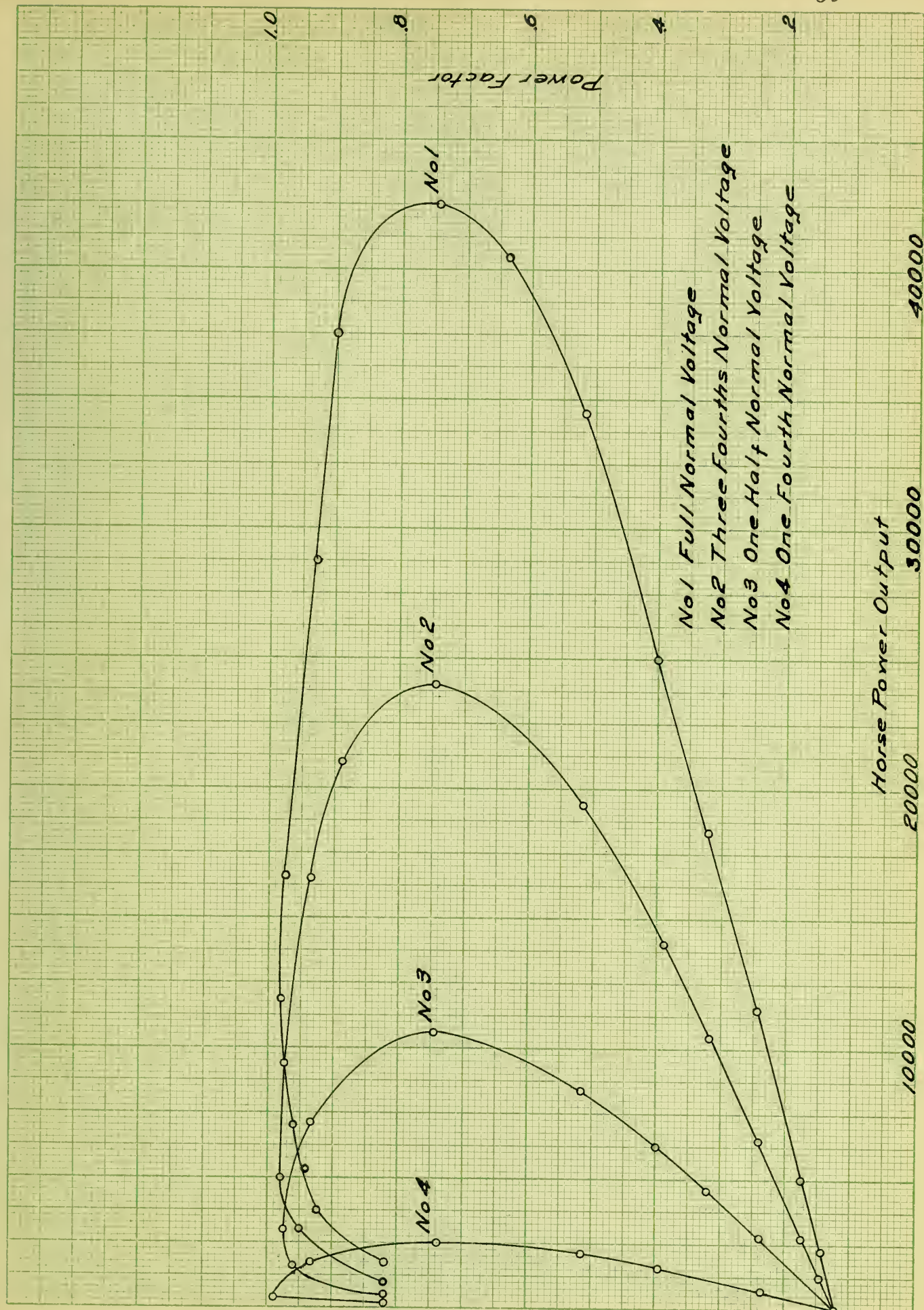
100

120

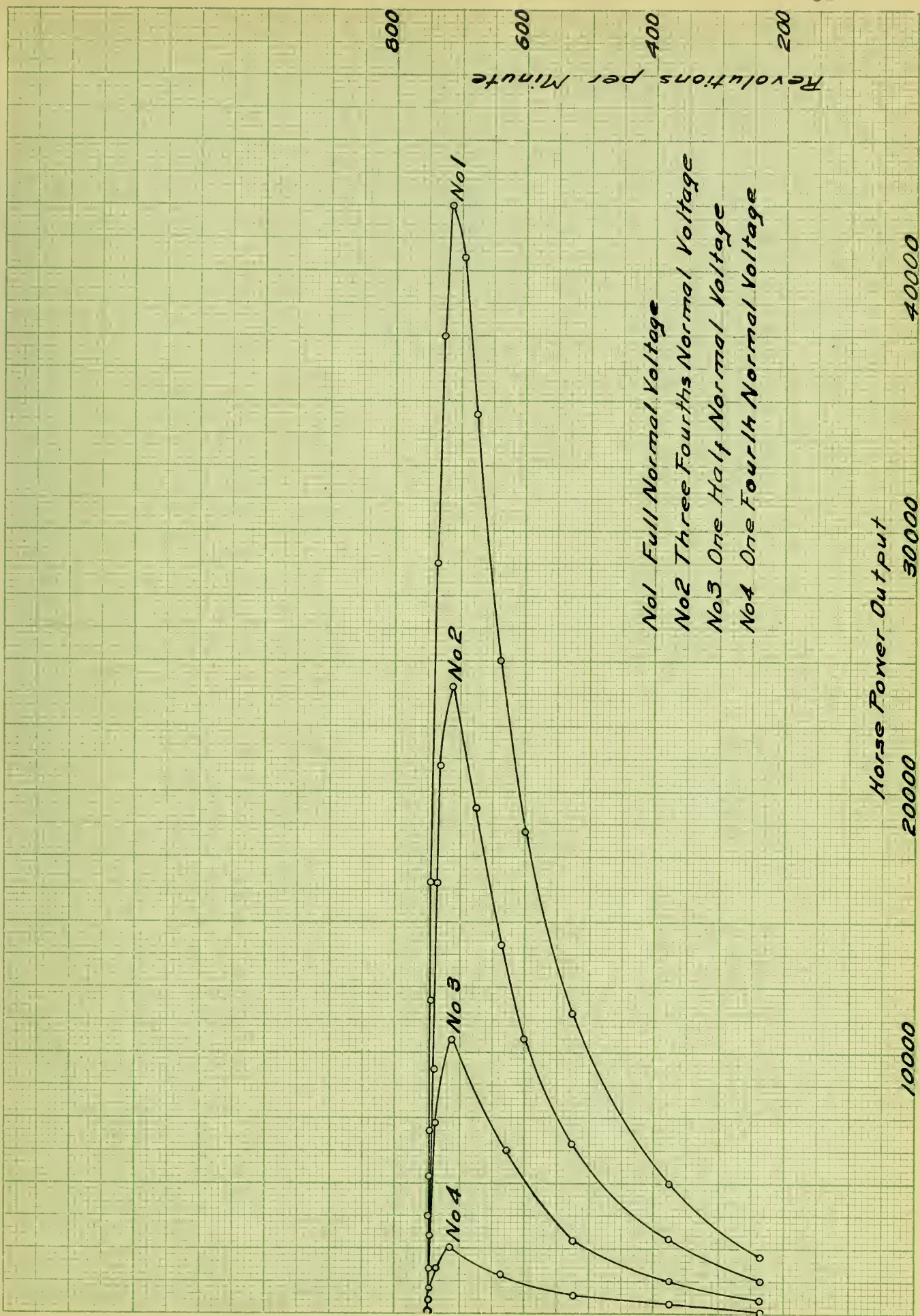














Efficiency - Percent

100

80

60

40

20

No 1

No 2

No 3

No 4

No 1 Full Normal Voltage  
 No 2 Three Fourths Normal Voltage  
 No 3 One Half Normal Voltage  
 No 4 One Fourth Normal Voltage

Horse Power Output

40000

30000

20000

10000



No1 Full Normal Voltage  
 No2 Three Fourths Normal Voltage  
 No3 One Half Normal Voltage  
 No4 One Fourth Normal Voltage

Apparent Efficiency Percent

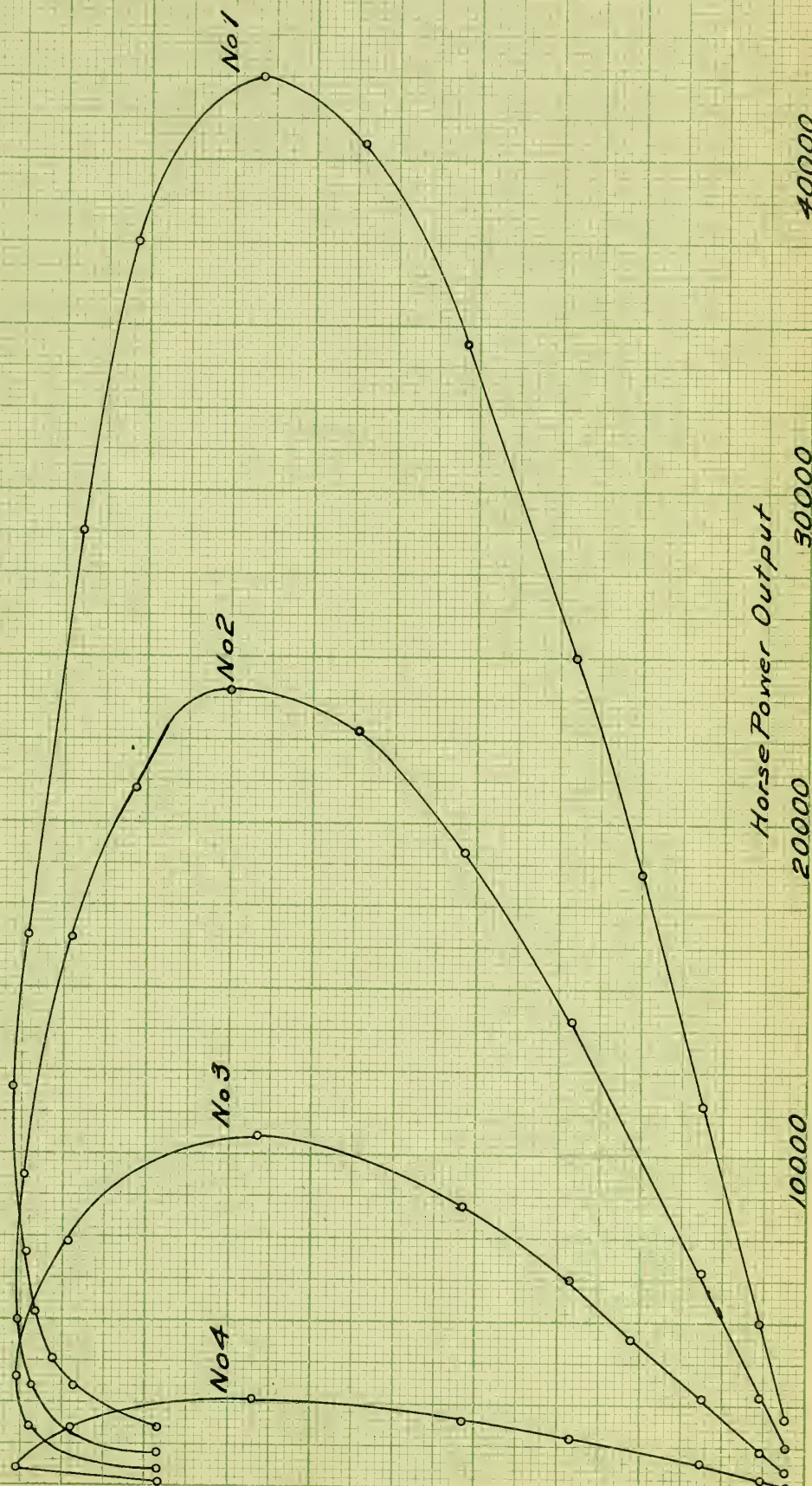
40000

30000

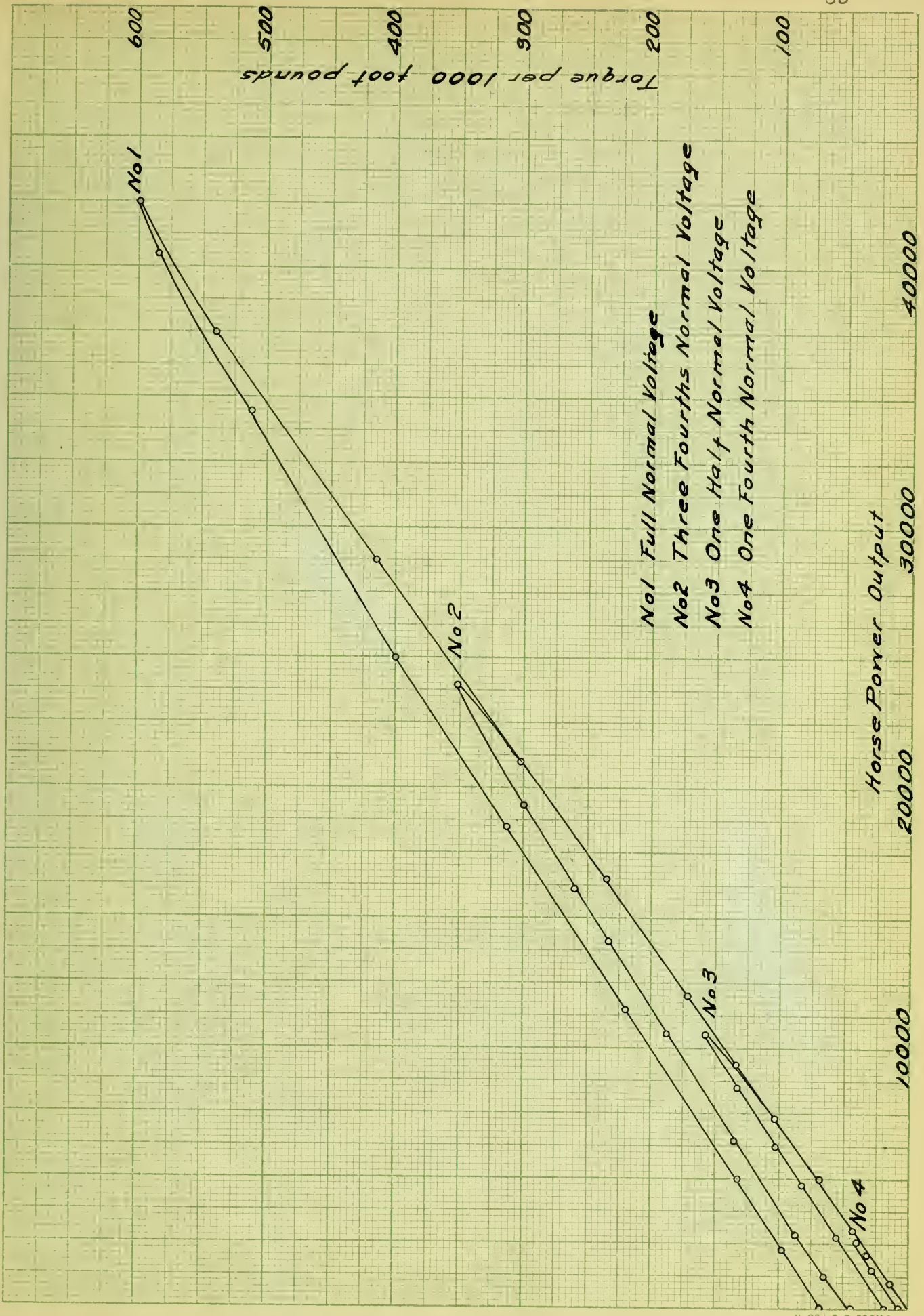
Horse Power Output

20000

10000









# Stator

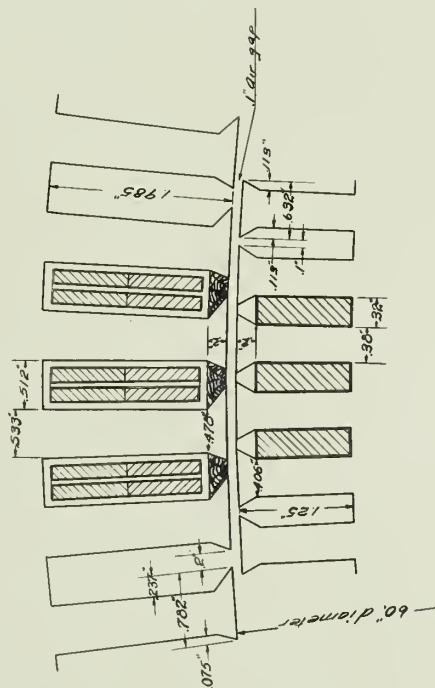
192 Slots. 1 turn per slot. Each conductor consists of 2 copper strip in parallel, separated by .005 inch mica insulation.

## Depth of Slot

200 inch	Wooden wedge
.080	Press board under wedge
.010	Mica cloth wrapped around conductors
.000	Copper Conductor
.005	Mica
.000	Copper Conductor
.010	Mica cloth wrapped around conductors
.080	Press board at bottom of slot
1.785	Total depth

## Width of Slot

.080	Press board on side of slot
.010	Mica cloth wrapped around conductor
.136	Copper conductor
.010	Mica cloth wrapped around conductor
.040	Press board between conductors
.010	Mica cloth wrapped around conductor
.136	Copper Conductor
.010	Mica cloth wrapped around conductor
.080	Press board on side of slot
.512	Total width



# Rotor

257 Slots. 1 Conductor per slot. Each conductor is a solid bar of copper.

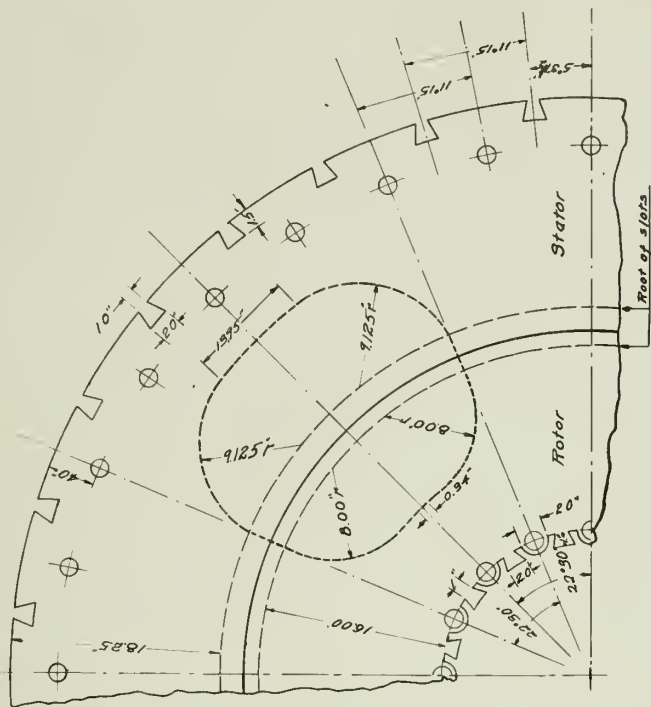
## Depth of Slot

200 inch	Press board wedge
.010	Shellac on conductor
1.030	Copper conductor
.010	Shellac on conductor
1.850	Total depth

## Width of Slot

.010	Shellac on conductor
.300	Copper conductor
.010	Shellac on conductor
.320	Total width

Scale: Full Size



Drawing shows shape of rotor and stator laminations. Heavy lines show mean length of magnetic flux. Scale: 1/8" = 10°







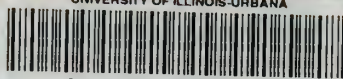
## LIST OF REFERENCES.

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- Hobart   and Ellis       Armature Construction.
- Fosters   Handbook .
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- Merriman   Mechanics of materials.
- Leutwiler and Duncan   Elementary Machine Design.
- Bearings       Machinery Reference Series.





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